WILHELM UND ELSE HERAEUS-STIFTUNG

666. WE-Heraeus-Seminar

From Correlation Functions to QCD Phenomenology

April 3 - 6, 2018
Physikzentrum Bad Honnef/Germany

Subject to alterations!

Introduction

The Wilhelm and Else Heraeus Foundation (Wilhelm und Else Heraeus-Stiftung) is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. To German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Scope of the 666. WE-Heraeus-Seminar:

The aim of this seminar is to bring together leading international experts and young researchers on topics such as

- confinement mechanism and dynamical chiral symmetry breaking
- hadron spectrum and dynamics of light quark bound states
- QCD phase structure and experimentally accessible observables

to present and discuss recent developments and fundamental issues.
The workshop focuses on theoretical aspects with methods ranging from Dyson-Schwinger equations and renormalisation group equations to lattice-QCD as well as effective field theory approaches. Furthermore, results of recent and prospects of future experiments will be discussed.

Scientific Organizers:

Prof. Cristina Aguilar	University of Sao Paulo, Brazil E-mail aguilar@ifi.unicamp.br Phone +55 193 5210 140
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Prof. Jan Pawlowski	University of Heidelberg, Germany E-mail j.pawlowski@thphys.uni-heidelberg.de Phone +49 6221 54 9429

Introduction

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Registration:

Jutta Lang (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Monday (17:00 h – 21:00 h) and
Tuesday morning

Door Code:

(Key symbol) 2 6 6 6 #

For entering the Physikzentrum
during the whole seminar

Program

Program

Monday, April 2, 2018

17:00 – 21:00	Registration	
from 18:30	*DINNER / Informal get together*	

Tuesday, April 3, 2018

08:00	BREAKFAST	
08:50 – 09:00	Scientific organizers	**Opening and welcome**
09:00 – 09:40	Craig Roberts	**Empirical manifestations of the source of visible mass**
09:40 – 10:20	Gernot Eichmann	**Baryon spectroscopy and structure in the Dyson-Schwinger approach**
10:20 – 10:45	Adnan Bashir	**From the QCD green functions to the internal structure of hadrons**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 11:40	Fabian Rennecke	**Fluctuations in 2+1 flavor QCD**
11:40 – 12:05	Jürgen Eser	**Low-energy limit of the O(4) quark-meson model**
12:05 – 12:30	Wei-jie Fu	**QCD phase transitions at finite temperature and densities within FRG approach**
12:30	**Conference Photo** (in the foyer of the lecture hall)	
12:45	*LUNCH*	

Program

Tuesday, April 3, 2018

15:00 – 15:40	Markus Huber	**2-, 3- and 4-point functions in 2, 3 and 4 dimensions**
15:40 – 16:20	Daniele Binosi	**Gluon mass generation: Theory and applications**
16:20 – 16:45	Fei Gao	**A trajectory of mesons' PDA corresponding to current quark mass**
16:45 – 17:15	COFFEE BREAK	
17:15 – 17:40	Ralf-Arno Tripolt	**In-medium spectral functions of hadrons with the Functional Renormalization Group**
17:40 – 18:05	Nicolas Wink	**Real time correlation functions at finite temperature**
18:30	*DINNER*	

Program

Wednesday, April 4, 2018

08:00	*BREAKFAST*	
09:00 – 09:40	Daniel Zwanziger	**A fresh look at QCD in Coulomb gauge**
09:40 – 10:20	Julien Serreau	**Perturbative dynamics of massive gluons**
10:20 – 10:45	Richard Williams	**Hadron spectroscopy from Dyson-Schwinger equations**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 11:40	Jan Maelger	**Heavy quark phase diagram at two-loop order in perturbation theory**
11:40 – 12:05	Antônio Pereira	**The Refined Gribov-Zwanziger scenario beyond the Landau gauge**
12:05 – 12:30	Matthieu Tissier	**Gribov copies, avalanches and dynamic generation of a gluon mass**
12:45	*LUNCH*	
	Time for discussions	
16:00 – 17:00	**Poster session** & *COFFEE*	
17:00 – 17:40	Mario Mitter	**QCD from gluon, quark, and meson correlators**
17:40 – 18:05	Marcus Bluhm	**Dynamics of net-baryon density correlations near the QCD critical point**
18:30	*DINNER*	

Program

Thursday, April 5, 2018

08:00	*BREAKFAST*	
09:00 – 09:40	Andre Sternbeck	**Three-point functions in Landau gauge from two-flavor lattice QCD**
09:40 – 10:20	Mariapaola Lombardo	**Weighted correlation functions and thermal widths**
10:20 – 10:45	Axel Maas	**The ambiguity of confinement**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 11:40	José Rodríguez-Quintero	**QCD 2- and 3-points Green's functions: From lattice gauge theories to phenomenology**
11:40 – 12:05	Martin Roelfs	**Spectral representation of lattice gluon and ghost propagators**
12:05 – 12:30	Paulo Silva	**Lattice ghost propagator in linear covariant gauges**
12:45	*LUNCH*	
15:00 – 15:40	Tereza Mendes	**Recent developments in lattice studies of IR propagators**
15:40 – 16:20	Lei Chang	**Pion and Kaon valence-quark quasiparton distribution**
16:20 – 16:45	Reinhard Alkofer	**Electromagnetic transition form factors of baryons in a relativistic Faddeev approach**
16:45 – 17:15	COFFEE BREAK	
17:15 – 17:40	René Sondenheimer	**Bound state spectrum of theories with a BEH effect**
17:40 – 18:05	Kei-Ichi Kondo	**Understanding quark confinement through a gauge-invariant Higgs mechanism**
18:05 – 18:20	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
19:00	*HERAEUS DINNER (cold & warm buffet, free beverages)*	

Program

Friday, April 6, 2018

08:00	*BREAKFAST*	
09:00 – 09:40	Hugo Reinhardt	**Variational approach to gauge theory**
09:40 – 10:20	Marlene Nahrgang	**Critical fluctuations in heavy-ion collisions**
10:20 – 10:45	Sergei Nedelko	**Domain wall networks and hadron properties**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 11:40	Bernd-Jochen Schaefer	**Mass sensitivity of the QCD phase structure**
11:40 – 12:05	Linda Shen	**Dynamical thermalization in the quark-meson model**
12:05 – 12:30	Dirk Rischke	**The extended Linear Sigma Model as a low-energy model for QCD**
12:30	Scientific organizers	**Poster awards and closing remarks**
12:45	*LUNCH*	

End of the seminar *and FAREWELL COFFEE* ***/ Departure***

Please note that there will be ***no*** *dinner at the Physikzentrum on Friday evening for participants leaving the next morning.*

Posters

Posters

1.	Lukas Corell / Markus Heller	**Flowing with time**
2.	Anton Konrad Cyrol	**Yang-Mills observables from correlation functions**
3.	Pascal Gunkel	**Quarks and pions at finite chemical potential**
4.	Philipp Isserstedt	**Taylor coefficients of the quark pressure from Dyson-Schwinger equations**
5.	Alexander Lehmann	**Real-time-evolution of heavy quarkonium-bound-states**
6.	Marc Leonhardt	**Symmetry breaking patterns in hot and dense QCD**
7.	Christian Söhngen	**Hybrids as three-body states from a Faddeev-equation**
8.	Paul Christian Wallbott	**Light tetraquarks in a Dyson-Schwinger/Bethe-Salpeter approach**
9.	Esther Weil	**Meson form factors in the Dyson-Schwinger approach**
10.	Savvas Zafeiropoulos	**Lattice QCD studies of pseudo-PDFs**
11.	Felix Ziegler	**Novel lattice simulations for transport coefficients in quenched QCD**

Abstracts of Lectures

(in chronological order)

Empirical manifestations of the source of visible mass

Craig D. Roberts

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QCD is the first theory to demand that science fully resolve the conflicts generated by joining relativity and quantum mechanics. In attempting to match QCD with Nature, it is necessary to confront the manifold complexities of strong, nonlinear dynamics in relativistic quantum field theory, e.g. the loss of particle number conservation, the frame and scale dependence of the explanations and interpretations of observable processes, and the evolving character of the relevant degrees-of-freedom.

The peculiarities of QCD ensure that it is also the only known fundamental theory with the capacity to sustain massless elementary degrees-of-freedom, gluons and quarks; and yet gluons and quarks are predicted to acquire mass dynamically so that the only massless systems in QCD are its composite Nambu-Goldstone bosons. All other everyday bound states possess nuclear-size masses, far greater than anything that can directly be tied to the Higgs boson.

These points identify and highlight the most important unsolved questions within the Standard Model, namely: what is the source of the mass for the vast bulk of visible matter in the Universe, how is its appearance connected with confinement; how is this mass distributed within hadrons and does the distribution differ from one hadron to another?

This presentation will highlight features of QCD's running coupling and masses, their impact on light-front wave functions and parton distributions, and some of the measurable consequences that follow. In doing so, it will identify a range of empirical observables whose measurement can potentially reveal pieces of the answers to the Standard Model's most pressing questions.

Baryon spectroscopy and structure in the Dyson-Schwinger approach

G. Eichmann

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I will discuss light and strange baryons obtained within the Dyson-Schwinger/Bethe-Salpeter approach. The experimental spectra of light octet and decuplet baryons are well reproduced in these calculations and their structure properties can be interpreted from their underlying diquark composition, which allows one to make predictions in the strangeness sector. I will address future paths regarding form factor calculations and the investigation of resonance dynamics and multiquark structure.

From the QCD Green Functions to the Internal Structure of Hadrons

A. Bashir

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Dynamical chiral symmetry breaking, responsible for almost all luminous massin the known universe, and confinement, are two emergent phenomena of strong interactions, not realized in perturbation theory at any order of approximation. Their study can be carried out naturally through QCD's fundamental field equations, i.e., Schwinger-Dyson equations to predict a host of hadronic observables. The fundamental building blocks of this study are the non perturbative propagators and vertices. Injecting them into the Bethe Salpeter equation, the internal structure of neutral pseudoscalar mesons is studied via two photon transition form factors, which evolve under the probing momentum of the photons. The resulting behavior is governed by the parton distribution amplitude and its evolution. The analysis is based upon a symmetry preserving Schwinger-Dyson and Bethe-Salpeter equations. Within a single systematic and consistent approach, with a traceable connection to QCD, the description of these transition form factors as well as pion elastic form factor, parton distribution amplitudes and many other properties is unified. We also argue how these quantities encode the footprints of chiral symmetry breaking and confinement. We provide our progress in the computation of some of the mesonic and baryonic transition form factors through Schwinger-Dyson equations.

References

[1] **"HEAVY QUARKONIA IN A CONTACT INTERACTION AND AN ALGEBRAIC MODEL: MASS SPECTRUM, DECAY CONSTANTS, CHARGE RADII AND ELASTIC AND TRANSITION FORM FACTORS"**, K. Raya, M. A. Bedolla, J.J. Cobos-Martínez, A. Bashir, arXiv:1711.00383

[2] **"PARTONIC STRUCTURE OF NEUTRAL PSEUDOSCALARS VIA TWO PHOTON TRANSITION FORM FACTORS",** K. Raya, M. Ding, A. Bashir, L. Chang, C.D. Roberts, **Phys. Rev. D95 No. 7 (074014:1-6) 2017.**

[3] **"η_c ELASTIC AND TRANSITION FORM FACTORS: CONTACT INTERACTION AND ALGEBRAIC MODEL"**, M.A. Bedolla, K. Raya, J.J. Cobos-Martínez, A. Bashir, **Phys. Rev. D93 (094025:1-10) 2016.**

[4] **"STRUCTURE OF THE NEUTRAL PION AND ITS ELECTROMAGNETIC TRANSITION FORM FACTOR",** K. Raya, L. Chang, A. Bashir, J.J. Cobos-Martínez, L.X. Gutiérrez-Guerrero, C.D. Roberts, P.C. Tandy, **Phys. Rev. D93 (074017:1-9) 2016.**

Fluctuations in 2+1 Flavor QCD

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Part of what makes the phase diagram of the strong interaction so intriguing is the rather large parameter space which determines its rich structure. We explore a subset of this space with focus on the low-energy sector of QCD with 2+1 dynamical quark flavors. The dependence of the phase structure and the related thermodynamic quantities on the quark masses, baryon and strangeness chemical potentials is discussed. We account for non-perturbative quantum fluctuations with the functional renormalization group.

Low-energy limit of the O(4) quark-meson model

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We compute the low-energy limit of the O(4)-symmetric quark-meson model as an effective field theory for Quantum Chromodynamics within the Functional Renormalization Group (FRG) approach. In particular, we analyze the renormalization group flow of momentum-dependent pion self-interactions beyond the local potential approximation. The numerical results for these couplings obtained from the FRG are confronted with a recent tree-level study. Additionally, their effect on the wave-function renormalization and the curvature masses is investigated.

QCD phase transitions at finite temperature and densities within FRG approach

Wei-jie Fu[1], Jan M. Pawlowski[2, 3] and Fabian Rennecke[2]

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[3] *ExtreMe Matter Institute EMMI, GSI, Planckstr. 1, 64291 Darmstadt, Germany*

We investigate the chiral phase transition and confinement-deconfinement phase transition at finite temperature and densities in two-flavor QCD. Quantum, thermal and density fluctuations, including those from the glue sector, are encoded through the functional renormalization group approach. The running strong and Yukawa couplings, from the perturbative to nonperturbative regimes, and their dependence on the temperature and densities, have been calculated. We also study the influence of the temperature and density on the gluon dressing function. Relevant results given in this talk will shed new light on the mechanism of the QCD phase transitions.

References

[1] Wei-jie Fu, Jan M. Pawlowski, and Fabian Rennecke, in preparation.

2-, 3- and 4-point functions in 2, 3 and 4 dimensions

M. Q. Huber[1,2]

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Results for Yang-Mills correlation functions in the Landau gauge from equations of motion of 1PI and 3PI effective actions are reviewed. The status of the truncation dependence is discussed on the basis of results for nonprimitively divergent correlation functions and for the three-dimensional case. Special emphasis is put on the renormalization of the underlying equations and perturbative resummation.

Gluon mass generation: Theory and Applications

D. Binosi[1]

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The nonperturbative dynamics leading to the generation of a gluon mass scale are inextricably connected with the formation of coloured composite massless excitations, which trigger the well-known Schwinger mechanism. First, I will elaborate on the subtle interplay between the Bethe-Salpeter equation governing the pole formation and the Schwinger-Dyson equation controlling the appearance of the mass scale at the level of the gluon propagator. Next, I will discuss how a renormalization-group invariant and process independent quantity may be constructed from first principles, which permits us to go beyond the traditional rainbow-ladder approximation, and serves as a bridge between "bottom-up" and "top down" approaches.

References

1. D. Binosi and J. Papavassiliou, arXiv:1709.09964 [hep-ph], Phys. Rev. D to appear.
2. A. C. Aguilar, D. Binosi, C. T. Figueiredo and J. Papavassiliou, Eur. Phys. J. C 78, no. 3, 181 (2018).
3. D. Binosi, L. Chang, J. Papavassiliou, S. X. Qin and C. D. Roberts, Phys. Rev. D 93, no. 9, 096010 (2016).
4. D. Binosi, L. Chang, J. Papavassiliou and C. D. Roberts, Phys. Lett. B 742, 183 (2015).

A trajectory of mesons' PDA corresponding to current quark mass

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The PDA can be defined as the light front projection of the Bethe-Salpeter wave function. It plays an essential role in the hard exclusive processes, where the scattering amplitude can be expressed with a hard scattering kernel that can be calculated perturbatively, and the PDAs of hadrons involved. Generally speaking, as the current quark mass increases, the PDA of the meson will become narrower with a simple no-humped distribution for the ground states. Therefore, the maximum value of the PDA can represent the inside structure of meson. There are two typical limits of this quantity, the compact point-like system with constant PDA which its maximum value is 1, and the heavy limit with PDA becoming delta function which the maximum value is infinite.

We investigated the maximum value of the symmetric PDA as the current quark mass increases from the light mesons to extremely heavy one and then found a surprising linear relation between this maximum value and the ratio of meson mass and decay constant for pseudoscalar meson. This linear relation holds for any flavours from u/d quark to extremely heavy quark, while there're no such relations in vector meson case.

In-medium spectral functions of hadrons with the Functional Renormalization Group

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We present an overview of recent results on in-medium spectral functions and transport coefficients of hadrons using the Functional Renormalization Group approach. Our method is based on a recently developed analytic continuation procedure that allows to calculate real-time quantities like spectral functions at finite temperature and chemical potential. Results for the quark, the sigma and the pion spectral function as well as for the shear viscosity over entropy density ratio are shown using the quark-meson model [1]. These quantities are studied in different regimes of the phase diagram, in particular near the chiral critical endpoint. Moreover, recent results for in-medium vector and axial-vector meson spectral functions are presented which are based on an extended linear-sigma model including quarks [2]. It is shown how the rho and the a1 spectral functions become degenerate at high temperatures and chemical potentials due to the restoration of chiral symmetry. Future applications of these recent developments are discussed, which include the calculation of dilepton spectra and the identification of experimental signatures of the chiral phase transition in the QCD phase diagram.

References

[1] R.-A. Tripolt, L. von Smekal, J. Wambach, Int. J. Mod. Phys. E **26,** 1740028 (2017)

[2] C. Jung, F. Rennecke, R.-A. Tripolt, L. von Smekal, J. Wambach, Phys. Rev. D **95** (2017) 036020

Real time correlation functions at finite temperature

J.M. Pawlowski[1,2] and N. Wink[1]

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The calculation of non-perturbative correlation functions at Minkowski frequencies in functional frameworks, including their analytic continuation at finite temperature, is discussed. The framework is embedded into the Functional Renormalization Group, enabling the possibility to unite state of the art truncations with inherent real time calculations. First results are presented, parts of which have been published recently in [1].

References

[1] N. Strodthoff, J.M. Pawlowski, N. Wink, arXiv:1711.07444 (2017)

A Fresh Look at QCD in Coulomb Gauge

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The Coulomb gauge condition $\nabla \bullet A=0$ leaves unfixed time-dependent gauge transformations, $g(t)$. These transformations are a symmetry of the first-order Euclidean action. We derive some elementary properties of propagators which are a consequence of this symmetry. In particular, the temporal components of the gluon propagator are found to have the simple instantaneous form $D_{A0,A0} = \delta(t)\ V_C(R)$, where $V_C(R)$ is the color-Coulomb potential. The Schwinger-Dyson equation is discussed.

Perturbative dynamics of massive gluons

J. Serreau[1]

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Lattice simulations of Yang-Mills theories and QCD in the Landau gauge have demonstrated that the gluon propagator saturates at vanishing momentum. This can be modeled by a massive deformation of the corresponding Faddeev-Popov Lagrangian known as the Curci-Ferrari model. The latter does not modify the known ultraviolet regime of the theory and provides a successful perturbative description of essential aspects of the non-Abelian dynamics in the infrared regime, where, in particular, the coupling remains finite, as also seen in lattice simulations. This opens the possibility of a controlled (semi)perturbative description of various aspects of the infrared QCD dynamics, ranging from correlation functions, to chiral symmetry breaking or the deconfinement phase transition at finite temperature and density. I review recent progress in this context.

Hadron spectroscopy from Dyson-Schwinger equations

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In QCD, the mass spectrum of both mesons and baryons arises as a result of the complicated interplay between their fundamental constituents, the quarks and gluons. It thus serves as one of several benchmarks for non-perturbative approaches to the strong interaction, and in particular the truncations necessary in the Dyson-Schwinger/Bethe-Salpeter approach [1,2].

In this talk we explore the efficacy of various truncations as a function of the total spin of the hadron. Together with an investigation of higher spin systems [3], we will explicate the role of the quark-gluon vertex as one example of a truncation scheme beyond that of one-gluon exchange [4]. In addition we will present recent progress in the calculation resonances in the Bethe-Salpeter framework [5].

References

[1] G. Eichmann, H. Sanchis-Alepuz, R. Williams, R. Alkofer, C. S. Fischer, *Prog.Part.Nucl.Phys. 91 (2016) 1-100*
[2] H. Sanchis-Alepuz, R. Williams, *arXiv:1710.04904*
[3] H. Sanchis-Alepuz, R. Williams, *in preparation*
[4] R. Williams, C. S. Fischer, W. Heupel, *Phys.Rev.D.93 (2016) 034026*
[5] *R. Williams, in preparation*

Heavy quark phase diagram at two-loop order in perturbation theory

J. Maelger[1,2], U. Reinosa[1] and J. Serreau[2]

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We study the QCD phase diagram with heavy quarks at finite temperature and (real or imaginary) chemical potential in the context of background field methods. The non-perturbative dynamics in the Yang-Mills sector is modeled by a phenomenological gluon mass term in the Landau-DeWitt gauge-fixed action. Various results [1] of extending a previous investigation [2] by including two-loop corrections to the background field effective potential will be presented and compared to non-perturbative approaches.

References

1. J. Maelger, U. Reinosa, J. Serreau, arXiv:1710.01930
2. U. Reinosa, J. Serreau, M. Tissier, Phys. Rev. D 92, 025021 (2015)

The Refined Gribov-Zwanziger scenario beyond the Landau gauge

A. D. Pereira[1]

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The existence of Gribov copies in the quantization of Yang-Mills theories is a well-known fact. A possible consistent way to remove (part of) these spurious configurations in the Landau gauge is realized by the so-called Refined Gribov-Zwanziger framework. In this talk, I will review this construction and introduce a recent extension to linear covariant and Curci-Ferrari gauges through the introduction of a gauge-invariant variable. This leads to a BRST-invariant, renormalizable and local action which takes into account the existence of Gribov copies beyond the Landau gauge. Some recent developments will be presented.

Gribov copies, avalanches and dynamic generation of a gluon mass

Matthieu Tissier, tissier@lptmc.jussieu.fr

Analytic calculations in the infrared regime of nonabelian gauge theories are hampered by the presence of Gribov copies which results in some ambiguity in the gauge-fixing procedure. This problem shares strong similarities with the issue of finding the true ground state among a large number of metastable states, a typical situation in the field of statistical physics of disordered systems. Building on this analogy, we propose a new gauge-fixing procedure which, we argue, makes more explicit the influence of the Gribov copies. A 1-loop calculation shows that the dynamics of these copies can lead to the spontaneous generation of a gauge-dependent gluon mass.

QCD from gluon, quark, and meson correlators

A. K. Cyrol,[1] M. Mitter,[2] J. M. Pawlowski,[1,3] and N. Strodthoff[4]

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We present non-perturbative first-principle results for quark-, gluon- and meson 1PI correlation functions of two-flavour Landau-gauge QCD in the vacuum [1] and Yang-Mills theory at finite temperature [2]. They are obtained by solving their Functional Renormalisation Group equations in a systematic vertex expansion, aiming at apparent convergence within a self-consistent approximation scheme. These correlation functions carry the full information about the theory and their connection to physical observables is discussed. The presented calculations represent a crucial prerequisite for quantitative first-principle studies of QCD and its phase diagram within this framework. In particular, we have computed the ghost, quark and scalar-pseudoscalar meson propagators, as well as gluon, ghost-gluon, quark-gluon, quark, quark-meson, and meson interactions and the magnetic and electric components of the gluon propagator, and the three- and four-gluon vertices. Our results stress the crucial importance of the quantitatively correct running of different vertices in the semi-perturbative regime for describing the phenomena and scales of confinement and spontaneous chiral symmetry breaking without phenomenological input. We confront our results for the correlators with lattice simulations and compare our Debye mass to hard thermal loop perturbation theory. Finally, applications to "QCD-enhanced" low-energy effective models of QCD are discussed.

References

[1] A. K. Cyrol, M. Mitter, Jan. M. Pawlowski, N. Strodthoff, arXiv:1706.06326 [hep-ph].

[2] A. K. Cyrol, M. Mitter, Jan. M. Pawlowski, N. Strodthoff, arXiv:1708.03482 [hep-ph]

Dynamics of net-baryon density correlations near the QCD critical point

M. Bluhm[1] **and M. Nahrgang**[2]

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Critical fluctuations in the net-baryon density play an essential role in the search for the QCD critical point. These form dynamically from intrinsic fluid dynamical fluctuations in the critical region. In this talk, we study the diffusive dynamics of the net-baryon density and show how long-range correlations develop within the framework of fluctuating fluid dynamics. We show under which conditions Gaussian and non-Gaussian correlations emerge from the consistent propagation of purely white noise. Real-time numerical simulations of the stochastic diffusion allow us to discuss the influence of exact baryon number conservation, of the finite size of the system and of non-equilibrium effects caused by its rapid evolution. This represents a crucial step toward a realistic modeling of critical point signals searched for at CERN-SPS and in the beam energy scan at RHIC.

Three-point functions in Landau gauge from two-flavor lattice QCD

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I will summarize recent lattice results for the quark-photon and the three-gluon vertex from two-flavor lattice QCD calculations.

Weighted Correlation Functions and Thermal Widths

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The focus of this talk is the behavior of bottomonium in media, in particular we address the issue of its thermal width. The starting point are the two point correlation functions computed by the FASTSUM collaboration. In our original work we have computed the spectral functions by use of a MEM analysis, and directly observed the broadening of the fundamental peak which gives the thermal width. This procedure however is subjected to some systematic uncertainty. Here we explore an alternative approach, by which we place bounds onthe thermal width by a few simple manipulations of the correlators.

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The ambiguity of confinement

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The quest to prove confinement runs since decades. However, the more attempts are made the less it becomes clear what really should be proven. In particular, many definitions of what should be proven are abound which apply only to a very small subclass of theories generally considered to be confining and/or only to particular particles in a theory.

The aim of this talk is not to provide an answer to any of these questions. Rather, it will be discussed, using especially scalar QCD(-like theories) as an example, that probably confinement is not a concept to provide physical insights. Rather, when starting from the physically observable spectrum of the theory it turns out that actually gauge invariance is the dominating concept. In fact, the elementary degrees of freedom then become reduced to their original purpose: To be auxiliary objects used to make a theory accessible to a (quasi-)local formulation.

QCD 2- and 3-points Green's functions: from lattice gauge theories to phenomenology

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We will shortly review the state-of-the-art for pure Yang-Mills and full QCD 2- and 3-points Green's functions from lattice calculations (e.g., the results for the 3-gluon vertex recently published in Refs. [1,2,3]), describe them by employing the Dyson-Schwinger equations' approach and exploit them, mainly within this latter approach, for phenomenological purposes as shown in Ref. [4,5].

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Spectral representation of lattice gluon and ghost propagators

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The Källén–Lehmann representation of propagators can be inverted to yield the spectral density of the field. But when applying this to (lattice) Gauge theories this inversion becomes ill-defined, due to the small singular values of the discretized integral kernel. One must also take into account the non-positive-definiteness of the spectral density of gluons and ghosts.

In order to overcome the problems associated with this ill-defined inversion, we shall apply various versions of Tikhonov regularization. To demonstrate the usefulness of this technique we discuss the results of applying this regularization to gluon and ghost propagators at zero temperature in Landau gauge. If time permits, we also discuss the generalization to finite temperature.

This talk is based on work-in-progress with David Dudal (KU Leuven-Kulak), Orlando Oliveira (UCoimbra) and Paulo Silva (UCoimbra).

Lattice Ghost Propagator in Linear Covariant Gauges

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We discuss the subtleties concerning the computation of the ghost propagator in linear covariant gauges on the lattice, together with preliminary numerical results.

Recent Developments in Lattice Studies of IR propagators

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We discuss different proposals for improving lattice simulations of infrared (IR) gluon and ghost propagators in Yang-Mills theories in Landau gauge. In fact, differently from analytic or numerical studies by functional methods, lattice simulations of Landau-gauge propagators suffer from severe finite-size corrections, which must be eliminated. At the same time, having access to the gauge configurations themselves in the course of the simulations offers an opportunity to gain insight into the geometry of the first Gribov region, thereby obtaining, hopefully, a clearer picture of the associated color confinement mechanism. These features are exploited to devise two unconventional approaches, based respectively on Bloch waves in crystalline solids and on properties of uncharacteristic gauge configurations, to achieve improved simulation results and a heuristic understanding of why the so-called scaling solution for IR propagators is not realized in lattice simulations.

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Pion and Kaon valence-quark quasiparton distribution

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We discuss the quasiparton distributions of pion and kaon by using an algebraic model. We focus on what is the lowest value of Pz to extract reliable information about the true distribution and how it is possible to catch the endpoint behavior. We find the ratio of kaon-to-pion quasi PDF provide a good approximation to the true ratio on $0.3<x<0.8$ and we expect that contemporary simulations of lattice QCD can deliver a reasonable prediction for this ratio before next generation experiments are completed.

Electromagnetic transition form factors of baryons in a relativistic Faddeev approach

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The covariant Faddeev approach which describes baryons as rel-ativistic three-quark bound states and is based on the Dyson-Schwinger and Bethe-Salpeter equations of QCD is briefly reviewed. All elements, including especially the baryons' three-body-wave-functions, the quark propagators and the dressed quark-photon vertex, are calculated from a well-established approx-imation for the quark-gluon interaction. Selected previous results of this ap-proach for the spectrum and elastic electromagnetic form factors of ground-state baryons' and resonances are reported. The main focus of this talk is a presenta-tion and discussion of results from a recent investigation of the electromagnetic transition form factors between ground-state octet and decuplet baryons as well as the octet-only Σ^0 to Λ transition.

Bound state spectrum of theories with a BEH effect

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The physical, observable spectrum in gauge theories is made up from gauge-invariant states. In QCD, confinement takes care of this issue while a gauge-invariant description of the spectrum in the weak sector is far from obvious. We demonstrate how the bound state spectrum can be mapped to the properties of the gauge-variant elementary fields in the electroweak sector of the standard model and discuss phenomenological implications.
In theories with a more general gauge group and Higgs sector this is no longer necessarily the case. We classify and predict the physical spectrum for a wide range of such theories, with special emphasis on GUT-like models, and show that discrepancies between the spectrum of elementary fields and physical particles frequently arise.

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Understanding quark confinement through a gauge-invariant Higgs mechanism

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We propose a gauge-independent description [1] of the Higgs mechanism [2] by which massless gauge bosons acquire their mass to become massive vector bosons. This is achieved without relying on the conventional spontaneous symmetry breaking signaled by a gauge-dependent vacuum expectation value of the scalar field. Instead the scalar field is supposed to obey a gauge-invariant condition, the radial length being fixed. We can include a gauge-invariant mass term in the pure Yang-Mills theory, and discuss quak confinement and mass gap in pure Yang-Mills theory from a viewpoint of the Higgs phenomenon in the gauge-scalar model and vice versa. Such an example was given for the adjoint scalar case for a gauge group SU(2) in [1].

In this talk, we extend this idea to include the fundamental scalar field. This extension enables one to discuss the crossover between Higgs regime and Confinement regime which are analytically continued without thermodynamic phase transition. Indeed, this result is a realization in the continuum of the statement made by Fradkin and Shenker, and Osterwalder-Seiler [3] in the gauge-invariant framework of lattice gauge theory for the gauge-scalar model with a constrained scalar field.

This allows one to decompose the original gauge field A into the massive vector mode W and the residual gauge mode V, A=W+V. In the fundamental scalar case, there are no massless gauge fields in the residual mode V after the Higgs mechanism occurs. In fact, we show that the residual gauge mode V has exactly the same form as the pure gauge V=iUdU with the group element U being formed from the scalar field F. Therefore the long-range force giving a linear static quark potential responsible for quark confinement must be mediated by the topological defect (soliton) represented by the pure gauge form, while the massive gauge mode W mediate only the short-range force. Based on the general framework given in the above, we demonstrate its validity in understanding confinement for various choice of the spacetime dimension D=2,3,4 and the gauge group G=U(1), SU(2), SU(2) x U(1).

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Variational Approach to Gauge Theory

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I will review the covariant variational approach to Yang-Mills theory in Landau gauge and compare it with the variational Hamiltonian approach in Coulomb gauge. First I will treat the vacum sector. Then I will study the deconfinement phase transition by calculating the Polyakov loop potential.

Critical fluctuations in heavy-ion collisions

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The search for the critical point of QCD is one of the main goals of the beam energy scan at RHIC and the CERN-SPS. In equilibrium, correlations diverge at the critical point leading to large event-by-event fluctuations in conserved quantities. For expanding systems like in heavy-ion collisions it is important to study the dynamical formation of long-range correlations in the critical region.
We have developed a model of chiral fluid dynamics which couples the explicit evolution of the fluctuations of the chiral critical mode to a full fluid dynamical expansion of a heavy-ion collision. Thermodynamic results from underlying QCD effective models are thus modified in the presence of a dynamical evolution.
In this talk, we discuss the relation between equilibrium and nonequilibrium expectations for the critical fluctuations of the chiral mode and the net-baryon number or the experimentally accessible net-proton number.

Domain wall networks and hadron properties

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Domain wall networks, motivated by consideration of the quantum effective action of QCD, is used to construct the statistical ensemble of almost everywhere homogeneous Abelian (anti-)self-dual gluon fields. Various characteristics of the ensemble such as mean topological charge, two point correlation functions of topological charge density, topological susceptibility are studied numerically. In particular the area law for the Wilson loop is demonstrated. The purpose of the present paper is to elaborate the properties of the domain wall network in much more details than it has been done previously. A brief overview of the correlation functions of gluon and quark fluctuations in the background of these networks and the phenomenological consequences for hadron spectra and form factors is given to underline their potential importance of the discussed gluon configurations for understanding the nonperturbative QCD vacuum structure.

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Mass Sensitivity of the QCD Phase Structure

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QCD at finite temperatures and densities predicts a phase transition from a chiral symmetry broken hadronic phase to a chirally restored quark-gluon plasma phase. In this talk the quark mass sensitivity of the three quark flavor chiral phase transition with and without an axial U(1)-symmetry breaking is addressed and investigated in the framework of a low-energy QCD effective model realization. The inherent ambiguities in fixing the low-energy model parameters away from the physical mass point and their consequences for the spontaneous chiral symmetry breaking are discussed in detail. Non-perturbative quantum fluctuations are taken into account with the functional renormalization group method. The influence of vacuum and thermal fluctuations of quarks and mesons on the order of the chiral phase transition is additionally assessed and confronted with mean-field approximations, where such fluctuations are typically ignored.

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Dynamical Thermalization in the Quark-Meson Model

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Understanding the early out-of-equilibrium dynamics of heavy-ion collisions (HIC) remains one of the biggest theory challenges. So far, there are no first principle calculations for the equilibration process of the quark gluon plasma and the dynamics close to the phase transition. In particular describing the behavior close to the conjectured critical point, where critical slowing down leads to off-equilibrium dynamics, poses difficulties.

Here we study the initial stages of a HIC using a low-energy effective theory of QCD, the quark-meson model, in order to gain insight into the thermalization process. This model manifests a central and physically relevant feature of QCD: chiral symmetry breaking in vacuum and its restoration at finite temperature and density. At the critical endpoint this model is expected to be in the same universality class as QCD and hence a viable model to explore dynamical critical phenomena.

We solve the non-perturbative real-time quantum equations of motions for the quark and meson fields in the two-particle irreducible effective action framework, i.e. coupled evolution equations for the macroscopic field and the two-point correlation functions. Similar to a HIC, our system is prepared in a high-energy initial state and suddenly quenched out of equilibrium, evolving towards a thermal final state in the chirally broken phase.

In a first step, we investigate the time-evolution of both bulk and spectral properties of this system, which provides us with insight into the approach of thermalization over time and the properties of the relevant degrees of freedom dominating the real-time dynamics. For the thermal final state, this implies information about the mass spectrum and the thermalization temperature. Finally, the prospects of generalizing the simulations to finite baryon density and the approach to the critical point are discussed.

The extended Linear Sigma Model as a low-energy model for QCD

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The chiral symmetry of QCD is spontaneously broken in the vacuum by a non-vanishing quark condensate. At sufficiently high temperature and chemical potential, this symmetry is effectively restored. A signal of chiral symmetry restoration is the degeneracy of chiral partners in the hadronic mass spectrum. In order to study chiral symmetry restoration in a theoretical approach, a linear sigma model is particularly well suited, as it treats chiral partners on the same footing.
In this talk, such a model, termed "extended Linear Sigma Model" (eLSM), will be presented, which features scalar and vector mesons as well as baryons (and their chiral partners) and respects the chiral and dilatation symmetries of QCD. A fit of the coupling constants of this model to hadronic vacuum properties reveals a surprisingly good agreement with experiment [1]. A consequence of this fit is that the scalar-isoscalar resonances $f_0(1370)$ and $f_0(1500)$ are identified as chiral partners of the pions and the η-meson. The $f_0(1710)$ resonance is (predominantly) a glueball state [2]. The light scalar-isoscalar resonances $f_0(500)$ and $f_0(980)$ are then resonances that are dynamically generated through the interaction of pseudoscalar mesons [3]. Incorporating $f_0(500)$ into the eLSM as an interpolating field, pion-pion as well as pion-nucleon scattering lengths can be reproduced as well [4]. It can be shown that the low-energy limit of the eLSM agrees with chiral perturbation theory [5]. Baryons are introduced as quark-diquark states with definite chiral transformation properties [6]. This naturally leads to four spin-1/2 baryon multiplets with definite transformation properties under parity. A consequence is that N(939) and N(1535), as well as N(1440) and N(1650) are chiral partners. The anomalously large decay width of N(1535) into N(939) and η can be interpreted as a consequence of the axial anomaly of QCD [7].

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Abstracts of Posters

(in alphabetical order)

Flowing with Time

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The time evolution of quantum fields out-of-equilibrium has many interesting applications ranging from cold atoms over heavy ion collisions to the early universe. In [1] and [2], a time evolution equation for the regularized 1PI-effective action was introduced based on ideas from the functional renormalization group. This equation is non-perturbative, manifestly causal and applicable in the classical as well as in the quantum regime. Causality is ensured by introducing a sharp cut-off regulator in the time domain which provides a gauge invariant regularization.
Using this method, we present first results for the propagator of a real scalar field with quartic self-interactions. In particular, we study the causal properties of the time flow equation in a numerical setup.

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Yang-Mills Observables from Correlation Functions

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Over the last few years significant progress in computing QCD correlation functions from the functional renormalization group has been made [1-5]. Although these gauge-fixed quantities are interesting and challenging on their own, only gauge-invariant quantities can be compared to experiments. On this poster, we present recent progress towards such observables. In particular, we report on first results for the trace anomaly as well as the pressure. Moreover, we show new results for the gluon spectral function.

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Quarks and pions at finite chemical potential

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We report on recent results on the the phase structure of strongly interacting matter, using the functional Dyson-Schwinger approach of QCD. Building upon previous works [1], we use different truncation schemes and explore their effects on the properties of the quark propagator and the resulting (pseudo-)scalar mesons at finite chemical potential. We discuss results for the masses, wave functions and decay constants below and above the first order transition at T = 0 and study the validity of the Silver Blaze property.

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Taylor coefficients of the quark pressure from Dyson-Schwinger equations

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We report on an investigation of the Taylor coefficients of the quark pressure using the non-perturbative framework of Dyson-Schwinger equations. The rainbow-ladder truncation is used to get a closed system of equations for the quark propagator and the derivatives of the latter with respect to the chemical potential are calculated self-consistently instead of using a difference quotient. We compare our results for the second and fourth coefficient to a previous Dyson-Schwinger study and results from lattice QCD.

Real-Time-Evolution of Heavy Quarkonium-Bound-States

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Elucidating the production process of heavy quark bound states is a central goal in heavy-ion collisions [1]. Two central questions exist:
Do bound states of heavy quarks form in the early time evolution of the glasma? If so, in which time regime can that happen? An Answer requires the development of a non-perturbative treatment of the real-time-dynamics of heavy quarkonia.

Here we present preliminary results from a simulation of bottomonium dynamics in the glasma, based on the concept of quenched, classical statistical simulations for the gauge fields [2]. We employ lattice real-time NRQCD to order $1/(M_q a)^2$ to describe the bottomonium evolution [3,4].

By computing the time-evolution of spectral functions of bottomonium-channels we expect to identify the emergence bound states and their formation time in the evolving glasma.

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Symmetry breaking patterns in hot and dense QCD

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We discuss the fixed-point structure and symmetry breaking patterns of hot and dense QCD. In a functional renormalization group approach we employ a Fierz-complete set of four-quark interactions which are dynamically generated by the gauge degrees of freedom. Our study particularly addresses the phase structure at low temperature and large quark chemical potential, a region where the application of fully first-principles approaches is currently difficult at best. Here we find the phase boundary to be dominated by diquark degrees of freedom in contrast to the dominating chiral dynamics at lower quark chemical potential. This change of dominance is mirrored in the changing fixed-point structure of the corresponding couplings when the chemical potential is varied. Our study suggests that at large quark chemical potential the Fierz-complete set of four-quark interactions is of great importance, shifting the phase boundary to significantly higher temperatures as compared to Fierz-incomplete considerations. Furthermore, we consider the implications of the axial $U_A(1)$ anomaly and introduce sum rules to monitor the strength of axial $U_A(1)$ breaking close to and above the phase boundary.

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Hybrids as three-body states from a Faddeev-equation

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We report on recent progress in the description of hybrid states in the framework of Dyson-Schwinger/Faddeev equations [1]. Based on explicit solutions for the quark and gluon propagators and their interactions we formulate a three-body equation describing hybrids as bound states of non-perturbative quark, antiquark and gluon constituents.

This setup builds on the analogous three-body framework for baryons [2] that has provided very satisfactory results for the octet and decuplet spectrum [3]. We discuss the hybrid's constituents and report on first results for the emergent bound state properties.

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Light tetraquarks in a Dyson-Schwinger/Bethe-Salpeter approach

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Abstract. A number of bound states of the strong interaction with potential non-quark-antiquark nature are waiting to be understood within QCD. A prominent example are the light scalars with $(J)^{PC} = (0)^{++}$, which have been interpreted as tetraquarks already long ago. Recent four-body calculations in the Dyson-Schwinger/Bethe-Salpeter approach support the tetraquark hypothesis and find the σ meson to have a strong pion-pion component [1].

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Meson form factors in the Dyson-Schwinger approach

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Form factors are highly relevant physical quantities as they are required to predict decay rates and to determine the underlying structure of hadrons. They are indirectly measured in many types of experiments, such as KTeV at Fermilab or the COMPASS experiment at CERN[1,2]. As experiments continue to reduce uncertainties on such observables, it is important to match the effort on the theoretical side. We are calculating meson form factors solving a numerically truncated version of the Dyson-Schwinger and Bethe-Saltpeter equations. On my poster I summarize our recent publications on the meson transition form factor of the neutral pion to two virtual photons ($\pi 0 \rightarrow \gamma(*)\gamma(*)$). In the course of the study we were able to calculate the form factor in different kinematic regimes[3] and compare our results to experimental measurements for the singly virtual form factor ($\pi 0 \rightarrow \gamma(*)\gamma$)[4,5,6,7]. We furthermore performed calculations for other pion decays, such as the ($\pi 0 \rightarrow$ e+e-) decay. The ladder poses an open question as the current theoretical predictions and experimental measurements from KTeV differ[8,9]. In order to perform the calculation we used a numerical method[10], in which the integration contour is routed along a complicated path in the complex plane, which is expected to have application for other systems of such kind. Recent developments towards other meson form factors and decay rates will also be featured.

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Lattice QCD studies of pseudo-PDFs

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Ioffe-time distributions, which are functions of the Ioffe-time v, are the Fourier transforms of parton distribution functions with respect to the momentum fraction variable x. These distributions can be obtained from appropriate equal time, quark bilinear hadronic matrix elements which can be calculated from first principles via lattice QCD methods. Here, we present the first numerical results of the Ioffe-time distributions of the nucleon.

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Novel lattice simulations for transport coefficients in quenched QCD

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Transport coefficients, such as the temperature-dependent shear and bulk viscosities, are essential QCD ingredients in the hydrodynamical description of relativistic heavy-ion collisions. While the equation of state by now is known with high precision from lattice simulations, the extraction of the transport coefficients from Euclidean simulations is extremely challenging. In particular, the corresponding Kubo formula requires the evaluation of a spectral function at vanishing momentum, and hence a reliable spectral reconstruction from Euclidean data at low frequencies. In standard lattice simulations at finite temperature this reconstruction is based on the discrete Matsubara frequencies, and is -in practice- exponentially hard: the thermal part of the low frequency information is hidden in the thermal decay of the Euclidean data at large frequencies.

In order to overcome this limitation, we apply the novel approach for thermal fields on the lattice [1] to gauge fields [2]. The formalism operates in a non-compact imaginary time domain that leads to continuous imaginary time frequencies. The quantum evolution is formulated as an initial value problem and the thermal initial conditions are supplied by a standard lattice simulation.

We present results for the energy momentum tensor in SU(2) Yang-Mills theory and SU(3) quenched QCD, which show excellent convergence to the standard results at finite Matsubara frequencies. From the correlation functions, we extract the relevant spectral functions using the Bayesian BR method [3] and determine the shear and bulk viscosity over entropy ratios. The imaginary time data in the present novel approach are precise enough to allow for a conclusive discussion of transport peaks in the spectral functions. Results are presented for the confined and deconfined phase.

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